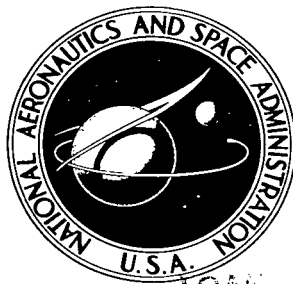


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INITIATION OF COOLING DUE TO BUBBLE GROWTH ON A HEATING SURFACE

by Robert C. Hendricks and Robert R. Sharp

Lewis Research Center

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SUMMARY

The surface temperature profile of a nickel-chrome-alloy heater strip during nucleate boiling was matched to high-speed photographic data. The initiation of surface cooling due to bubble growth was investigated and was discussed in relation to existing models of nucleate boiling. Experimental data indicate that, at moderate subcooling, evaporation from a surface liquid film accounts for most of the ebullient heat transfer. No increase in heat transfer due to microconvection or surface quenching by cold bulk liquid was observed.

INTRODUCTION

Much of the research concerning nucleate boiling during the past several years has been conducted in order to determine the mechanisms, evidently due to bubble formation, that are responsible for producing the high heat fluxes associated with boiling. A quantitative description of the heat-transfer process has by no means been accurately formulated at present. Of the several models of boiling that have been proposed, the most widely accepted models hypothesize that the bubble acts as an agitator of the liquid.

Rohsenow and Clark (ref. 1), Gunther and Kreith (ref. 2), and others have suggested that the principal path of heat transfer is from the surface through the turbulent liquid between bubbles. Since conduction through a laminar thermal layer is insufficient to account for observed heat fluxes, these workers have proposed that growing and collapsing bubbles create random microconvection currents of high velocity along the heated wall. In effect, agitation from the bubble is believed to destroy the thermal layer beneath the bubble and over some unknown distance around its base; this area of effective agitation is commonly referred to as the area of influence of a bubble. In the work of reference 3, in fact, it was observed by means of schlieren motion pictures that the thermal-layer thickness is greatly diminished during bubble growth within a distance of one bubble diameter around the nucleation site.

*An abbreviated version of this report was presented at the American Institute of Chemical Engineers meeting, Los Angeles, California, February 4-7, 1962.

These experiments give a clear definition of the region of effective forced convection due to a bubble.

Forster and Greif (ref. 4) have suggested that a more efficient heat-transfer mechanism occurs when a growing bubble displaces the superheated liquid layer entirely from the surface (fig. 1(a)). Cooling then occurs during collapse when cold liquid suddenly quenches the hot surface. Thus the heat-transfer mechanism would be a continuous cycle of vapor-liquid displacement with the surface heat flux increasing locally during the quenching process.

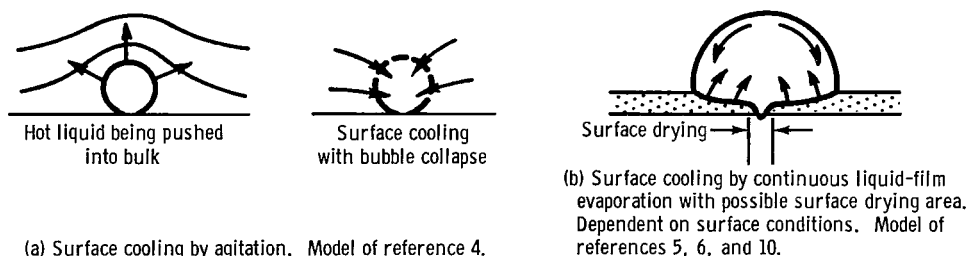


Figure 1. - Surface cooling effects in relation to bubble models.

Evaporation into the bubble is generally thought to occur from the liquid superheat layer pushed away from the surface by a growing bubble. As evaporation takes place, the layer cools and the rate of this process controls bubble dynamics. More recently, Snyder (ref. 5) and Edwards (ref. 6) have suggested that evaporation occurs chiefly from the base of the bubble, either from the perimeter of the base or from a thin liquid film left on the surface during bubble formation. Rapid evaporation from the base would have the effect of drawing large amounts of heat directly out of the boiling surface during bubble growth (fig. 1(b)).

The contribution to the total heat transfer due to evaporation into the bubble has, in general, been considered small if not negligible. Rohsenow and Clark (ref. 1) have made measurements of bubble volumes from motion pictures and have compared the latent heat associated with the observed vapor flux with the total heat flux. Their results indicate that evaporation accounts for no more than 1 to 2 percent of the total heat transfer. These workers, however, ran boiling tests in the subcooled regime and did not correct for condensation in the growing bubble. Bankoff (ref. 7) measured condensation rates of steam bubbles and concluded that the vapor evolved is probably 10 times greater than the amount observed by Rohsenow and Clark. This still indicates only a minor role for an evaporative mechanism in the total heat transport.

Most important to the support of a bubble agitation theory, however, would be a direct indication that bubble dynamics is sufficient to increase heat fluxes to levels observed in nucleate boiling. It was reasoned in the study of reference 8 that streams of air bubbles that were electrolytically generated on a heated surface should simulate the agitation over a boiling surface while the evaporative heat transport is virtually eliminated. The air bubbles were indeed found to have a strong effect on the heat-transfer coefficient, but no heat fluxes comparable to vigorous nucleate boiling were ever attained.

Another, but quite indirect, source of support for an agitation theory is the application of several semitheoretical correlations (ref. 9) that are based on a forced convection (modified Nusselt number) relation. This type of correlation has given fairly good results.

Moore and Mesler (ref. 10) sought more direct evidence concerning the mechanism of boiling heat transfer by observing the temperature-time profile of a boiling surface with a high-response thermocouple read by an oscilloscope. They noted regularly an exceedingly rapid drop in temperature followed by a smaller rapid rise and a gradual reattainment of the initial temperature. Moore and Mesler did not know whether these drops occurred with the same frequency as bubble formation, nor did they have any indication of where, with respect to bubble growth, the temperature drops began. The rapidity of cooling immediately suggested an evaporation phenomenon, although similar temperature behavior would be expected on the flooding of a hot surface with cold liquid. They calculated the maximum heat flux obtainable from surface flooding and found this to be insufficient to account for the magnitude of the temperature drop. They also calculated that between 70 and 90 percent of the total heat transfer could be attributed to the temperature drop. This indicates that, if the drop is indeed caused by evaporation, latent heat transport is many times as important in the boiling phenomenon as had been thought previously. Certainly such a drop is an outstanding characteristic of the microlayer model of evaporation described by Snyder (ref. 5) and Edwards (ref. 6).

Both the quantitative and the qualitative conclusions of Moore and Mesler are open to considerable doubt, however, since the construction of their thermocouple caused a heating discontinuity.¹ Still, it is evident that a rapid drop in surface temperature does occur during boiling and that this drop is probably associated with an appreciable portion of the total heat flux.

In this report high-speed photographic data have been matched with the surface temperature-time profiles underneath large discrete bubbles in order to determine when, with respect to bubble life, local fluctuations of surface heat flux occur. In particular, it was desired to determine exactly where in the ebullition cycle the large temperature drop noted by Moore and Mesler begins. If the drop occurs at the incipience of bubble growth rather than during departure, it will be caused by evaporation at the bubble base. The agitation and the liquid microlayer hypotheses are discussed in relation to the observed temperature fluctuations during the ebullition cycle. Absolute magnitudes of the temperature drop were also measured, and the resultant local

¹The thermocouple used in the investigation of reference 10 consists of an electrically insulated Alumel wire core passing through a Chromel cylinder, which in turn is attached to an electrically heated surface. While the Chromel cylinder dissipates heat at a rate comparable to the homogeneous heater, the Alumel wire core does not dissipate electrical energy. Hence, the core wire is heated only by conduction from the surrounding material. Heat removal from this core wire during a temperature fluctuation would occur at a greater rate than from the Chromel cylinder, and a temperature gradient across the thermocouple junction would result. Consequently, the thermocouple would not read correctly, although the thermocouple would respond well to temperature pulses.

heat fluxes were calculated. From these data several conclusions have been reached concerning the relative quantitative importance of the agitation and the evaporative heat-transfer mechanisms.

The results of this experiment are applicable to the boiling cases of discrete bubbles and bubble columns when subcooling does not exceed about 30° F. Conclusions regarding microconvection and quenching might be inaccurate at higher subcoolings. The poorly understood regime of vapor columns also requires further investigation.

SYMBOLS

cs	camera speed
L	heater length
l	heater thickness
q	heat flux
q_{gen}	generated heat flux
T	temperature
T_{max}	maximum temperature
T_{sat}	saturation temperature
t	time
$t_{\text{rm},1}$	reference time for mechanical system with bubble occurring before reference mark
$t_{\text{rm},2}$	reference time for mechanical system with bubble occurring after reference mark
$t_{\text{ro},1}$	reference time for optical system with bubble occurring before reference mark
$t_{\text{ro},2}$	reference time for optical system with bubble occurring after reference mark
t_{ϕ}	phase lag
t_0	system time response
V	voltage
x	number of frames from reference timing mark to initiation of bubble

y number of frames until bubble crosses thermocouple location
 z heater coordinate
 α thermal diffusivity
 θ temperature
 ϕ transformer phase change, sec

APPARATUS AND PROCEDURE

The data-recording system is shown schematically in figure 2. In order to

ensure that the test fluid was free of foreign materials, the vessel was purged of air and was loaded with distilled, degassed water. The desired degree of subcooling was obtained by drawing a vacuum in the vessel. Two types of electrically heated Nichrome elements were used. The first was 0.0056 inch thick and 1/16 inch wide, and the second was 0.001 inch thick and 1/8 inch wide. The heated length of each element was $1\frac{7}{16}$ inches. The

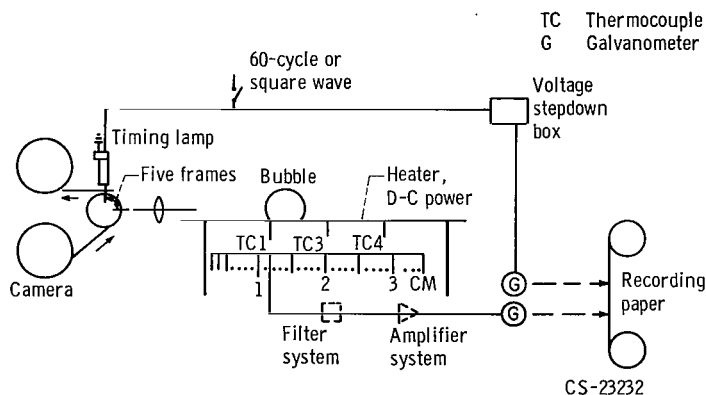
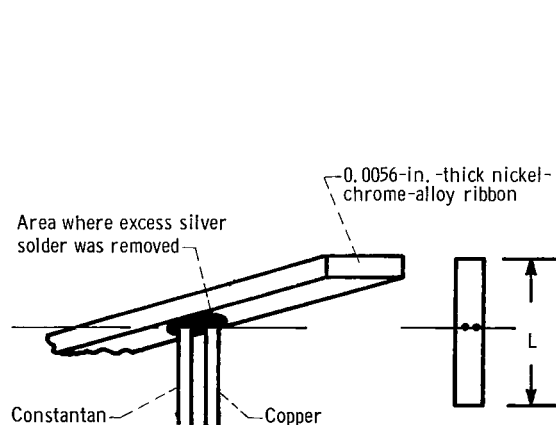
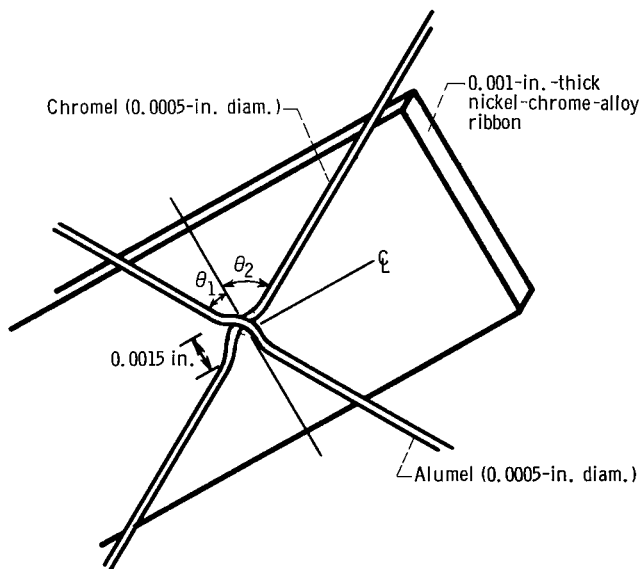


Figure 2. - Data-recording system.



(a) Copper-constantan thermocouple. Voltage gradient $\partial V / \partial L$, 0.



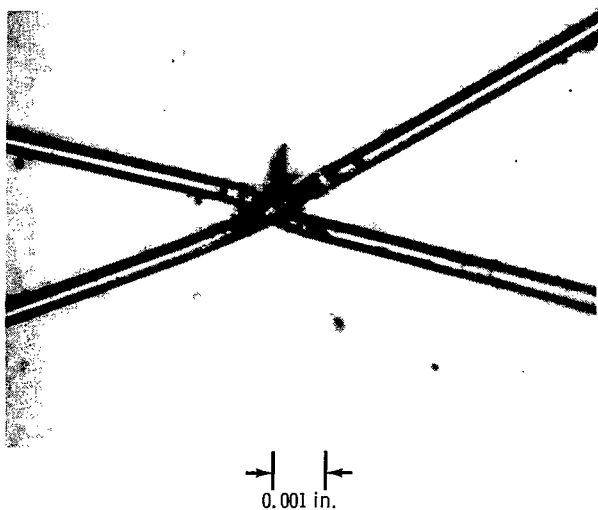
(b) Chromel-alumel thermocouple $\theta_1 = \theta_2$.

Figure 3. - Thermocouple installations.

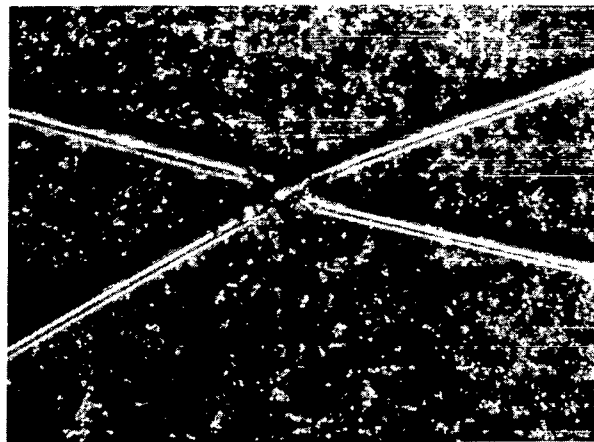
Nichrome ribbons were mounted on a block that insulated the lower surface.

The first element (0.0056 by $\frac{1}{16}$ by $1\frac{7}{16}$ in.) was relatively heavy in construction and was used to observe qualitatively the temperature fluctuations during the ebullition cycle. Three 36-gage copper-constantan thermocouples were silver soldered to the heater subsurface, and the excess silver solder was removed from the area indicated in figure 3(a). This method of attachment provides a surface with no discontinuity, but involves a heater nonhomogeneity. The absolute values of the temperature readings at the subsurface are not considered reliable, but the subsurface readings corrected for time response are reliable in showing temperature fluctuations.

The second element (0.001 by $\frac{1}{8}$ by $1\frac{7}{16}$ in.) was capable of measuring temperature profiles with far greater accuracy than the first. Since the thermocouple acted as a heat sink and disturbed the heat-flux pattern out of the strip, the 36-gage (0.005 -in.-diam.) copper-constantan leads were replaced with 0.0005 -inch-diameter Chromel-Alumel leads. Also, since any excess silver solder formed a path of low resistance to the heater voltage and created an area of lower heat generation, the Chromel-Alumel thermocouple was spotwelded at a point to the heater strip. The junction was made by crossing a Chromel and an Alumel wire and by spotwelding them to the strip at their point of contact as is shown in figure 3(b). A drop of epoxy cement was placed on the weld to give the two thermocouples strength and also to keep the lead wires away from the heater strip. The thermocouple junction shown in figure 3(b) was localized to an area of approximately 0.001 to 0.002 inch in diameter. A photomicrograph of the thermocouple junction is shown in figure 4. Direct-current pickup from the heater voltage was rather large, even across this tiny junction, but was determined by suitable calibrations.



(a) Light field illumination.



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(b) Dark field illumination.

Figure 4. - Welded thermocouple junction.

During each run, heater voltage and current, pool temperature, and pressure were measured. Subsurface temperatures were recorded on an oscillograph, and motion pictures were taken simultaneously with a high-speed camera. Subatmospheric pressures yielded larger bubbles, which facilitated the study of single bubbles.

Determination of Time Base

Correlation of the time base is a problem that arises when data are recorded simultaneously by camera and oscillograph or oscilloscope. Time shifts may occur because of phase changes, recording-circuit lags, lamp response to applied voltage, heater thickness, or thermocouple current output.

Time Lags in Sensing Temperatures

When a temperature fluctuation occurs on the upper surface of the heating strip, a finite time passes before this fluctuation influences the subsurface temperature. An approximation to the subsurface temperature pulse may be obtained by reducing the general transient heat-conduction equation to

$$\frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial z^2} \quad (1)$$

where

$$\theta = T \quad z = l$$

$$\frac{\partial \theta}{\partial z} = 0 \quad z = 0$$

$$\theta = 0 \quad z = 0 \quad t = 0$$

This equation does not include a heat-generation term but is considered adequate since the local heat flux during the rapid temperature drop is more than one order of magnitude greater than the average electrical heat flux (fig. 7). Solutions of equation (1) along with a parametric plot of T/T_{\max} against z/l for successive values of $\alpha t/l^2$ are shown in figure 11 of chapter 3 in reference 11. For a sudden change in temperature on the boiling surface, the ratio of subsurface (thermocouple) temperature to the maximum change in surface temperature may be determined at any given time.

To sense a change in temperature, rather than its absolute value, the plots of reference 11 can be consulted to determine the time interval between the initiation of a pulse and the time when a measurable temperature change occurs on the subsurface. This time lag is approximately 1.1 milliseconds for the 0.0056-inch-thick heater, an appreciable correction, but only 0.036 millisecond for the 0.001-inch-thick heater.

Since the thin heater was used to measure absolute values of the temperature profile, it is important to show that, during any actual temperature fluctuation on the boiling surface, the subsurface temperature will approach the supersurface temperature in a very short time compared with the total duration of the temperature change. This temperature lag across the heater will have the greatest magnitude when an instantaneous temperature pulse is applied to the upper surface. The solution of this problem also can be found in the curves of figure 11 of chapter 3 in reference 11. For a pulse of any magnitude, 90 percent of the total temperature change is observed on the subsurface within half a millisecond. By comparison with the temperature profile (fig. 7), which has a duration of 15 milliseconds, it is apparent that the supersurface drop is far from instantaneous and that this drop must be quite close to the one actually sensed by the thermocouple.

The heat capacity of the thermocouple itself is not considered to be an appreciable source of error since the dimensions of the junction are small compared with the heater thickness. With certain corrections for the effects of electrical pickup, the temperature profiles sensed by the thermocouple are considered to yield accurate absolute values.

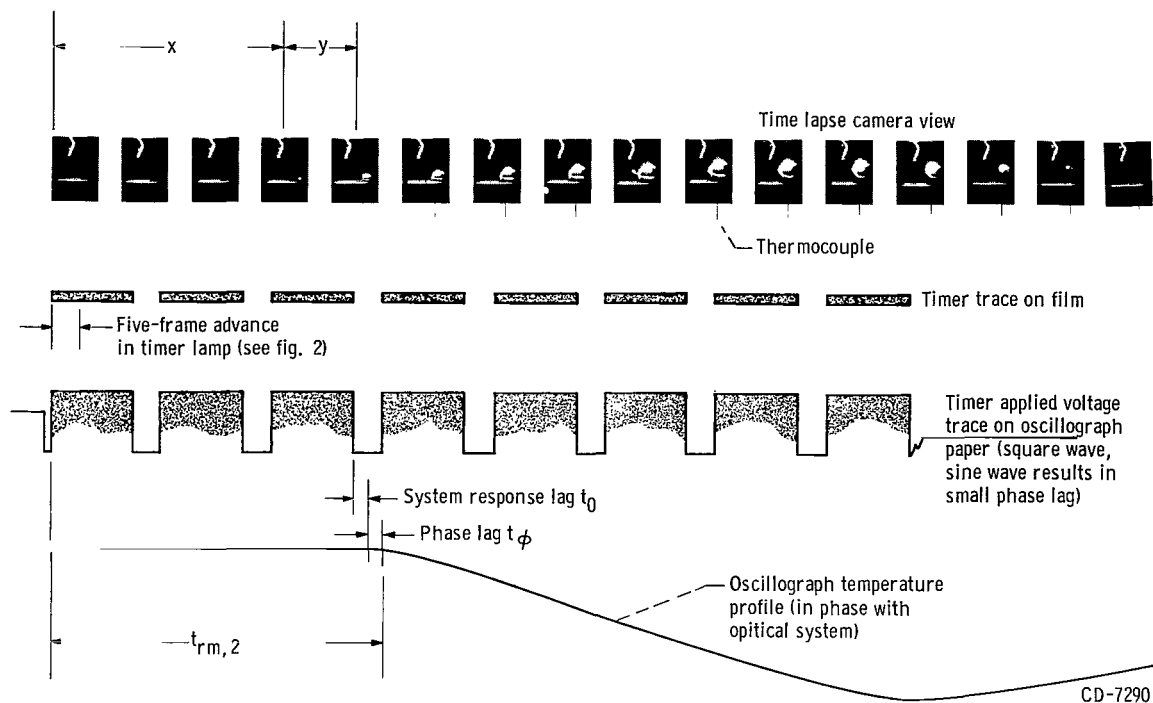
Oscillograph Recording System

During the course of the experiment three types of thermocouple recording systems were used. In the first system a 400-microfarad damping capacitor, which increased the system delay time but reduced pickup, was wired in parallel with a 40-cycle galvanometer. In the second system pickup was reduced and the large capacitor was eliminated; consequently, the time-delay error was lowered. In the third system, which was used for measuring absolute values of the temperature profiles, a direct-current differential amplifier impressed the thermocouple signal across a 400-cycle galvanometer. Control experiments² showed that this galvanometer was capable of much faster response than was required for any of the temperature fluctuations studied. The oscillograph, which was run at paper speeds of 50 inches per second, could be read easily to 0.01 millivolt and with relative accuracy to 0.005 millivolt. All known phase lags were eliminated where possible.

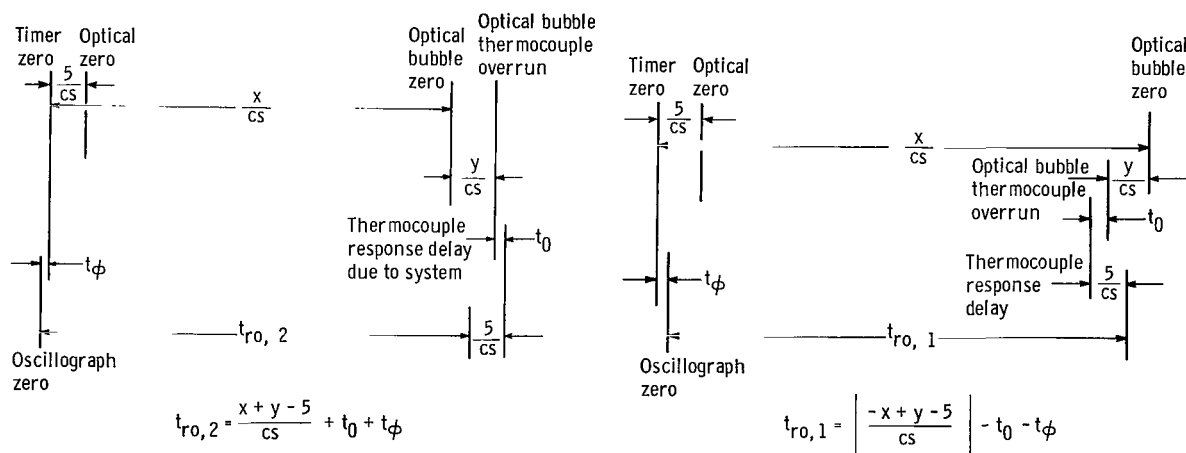
Optical System

The time lag of the film to the frame of light is very small; however, the reference timing light response depends on the applied voltage. When a 60-cycle voltage is used, the lamp may lag the applied voltage by 60°. After several runs were taken with this system, the 60-cycle timer was replaced by a square-wave timer because of reading and phase uncertainties in the 60-cycle system.

²In one experiment, a few drops of cold water were dropped on the heater surface at the thermocouple junction. The action was recorded by the high-speed camera, and the response was recorded by the oscillograph. The result was nearly a square wave response in temperature when the drop contacted the heater surface. In a second experiment, the response of a galvanometer to a square-wave audio-oscillator input was observed.



(a) Relations of optical and oscillograph systems.



(b) Reference time between optical- and oscillograph-recording systems with bubble occurring after reference timer mark (fig. 5(a)).

(c) Reference time between optical- and oscillograph-recording systems with bubble occurring before reference timer mark.

Figure 5. - Time base.

TABLE I. - OPTICAL AND MECHANICAL TIME CORRELATION MEASUREMENT

Number of frames from reference timing mark to initiation of bubble, x	Camera speed, cs, frames/sec	Number of frames until bubble crosses thermocouple location, y	System time response, t_0 , msec	Phase lag, t_ϕ , msec	Other phase changes, ϕ , msec	Optical system reference time, $t_{ro,2}$, msec	Mechanical system reference time, $t_{rm,2}$, msec	Bubbles
71	1380	5	1.5	1.1	6.6	42.4	44.5	1
59	2040	11	1.5	1.1	6.6	16.8	13.8	2
64	2160	1.4	1.0	1.1	6.6	16.8	15.5	3
17	1020	3	1.1	1.1	6.6	9.8	8.8	1
23	2100	8	1.5	1.1	0	6.9	2.9	1
36	1740	8	1.1	1.1	0	17.1	15.3	2
99	2190	6	.8	1.1	0	46.6	50.0	3
226	1873	3	0.8	1.1	0	119.9	120.7	1
^a 200	1783	3	.8	↓	↓	112.4	112.7	1
^a 192	1900	10	1.5	↓	↓	108.9	110.5	1
213	1900	10	1.5	↓	↓	107.1	106.2	1
^a 241	1836	2	.8	↓	↓	131.5	129.1	2
164	1895	2	.8	↓	↓	86.2	87.7	2
111	1753	2	0.8	0	0	63.2	62.4	1
0	2163	13	.8	0	0	4.5	6.6	2
60	2240	3	0.8	0	0	26.7	29.0	1
^a 94	884	1	0.8	0	0	102.6	100.1	1
97	917	1	↓	↓	↓	109.3	107.0	1
^a 114	1050	1	↓	↓	↓	105.6	105.4	2
60	1050	1	↓	↓	↓	60.2	56.0	2
^a 7	117	2	↓	↓	↓	4.4	4.2	3
179	1125	2	↓	↓	↓	161.0	158.9	3
111	850	1	↓	↓	↓	136.0	142.6	1
^a 198	1644	7	↓	↓	↓	122.4	127.2	2
49	1688	7	↓	↓	↓	27.0	23.4	2
^a 120	1097	1	↓	↓	↓	106.5	103.6	1
89	1206	1	↓	↓	↓	76.3	74.3	1
^a 216	1950	3	↓	↓	↓	110.5	111.4	2
107	1968	3	↓	↓	↓	54.6	58.2	2
^a 23 $\frac{1}{2}$	1096	1	0.8	0	0	18.6	20.6	2
56	1096	1	.8	0	0	52.7	51.8	2
22	1517	2	.8	0	0	13.2	16.2	1

^aBubble occurred after reference timer mark rather than before timer mark.

A voltage divider placed the voltage impressed on the timing lamp across a galvanometer. The lag of the square-wave timing-lamp circuit in recording on the galvanometer was considered small. A constant five-frame timer-lamp advance with respect to the bubble history is caused by the position of the lamp in the camera (fig. 2).

On the basis of these time relations, the reference time between optical- and oscillograph-recording systems may be summarized as shown in figure 5. If the reference time based on the optical system ($t_{ro,2}$ or $t_{ro,1}$) equals the time measured on the oscillograph paper ($t_{rm,2}$ or $t_{rm,1}$), the action occurred exactly as predicted from the observation

$$t_{ro,2} = \frac{x + y - 5}{cs} + t_0 + t_\phi + \phi \quad (\text{fig. 5(b)})$$

$$t_{ro,1} = \left| \frac{-x + y - 5}{cs} \right| - t_0 - t_\phi - \phi \quad (\text{fig. 5(c)})$$

where x is the number of frames from the reference timer mark to the initiation of the bubble, y is the number of frames it takes the bubble front to cross over the thermocouple location, cs is the camera speed in frames per second, and t_0 and t_ϕ are system response time and phase lag, respectively; ϕ is a 135° phase lag, which occurred in one run in the 60-cycle timer because of a nongrounded transformer. A segment of an actual oscillograph trace (fig. 6) is marked to illustrate these time delays. The measurements taken appear in table I.

DISCUSSION

When high-speed motion pictures of nucleate boiling (heat flux, approx. 25,000 Btu/(hr)(sq ft)) were matched to the surface temperature profiles, a rapid temperature decrease associated with bubble growth was observed. This temperature decrease, comparable to that noticed by Moore and Mesler (ref. 10), had four important characteristics:

(1) The time relations in table I show that the drop occurred as soon as the perimeter of the bubble base passed over the thermocouple junction. The error in these measurements is approximately ± 2 milliseconds, a short time compared with the bubble life.

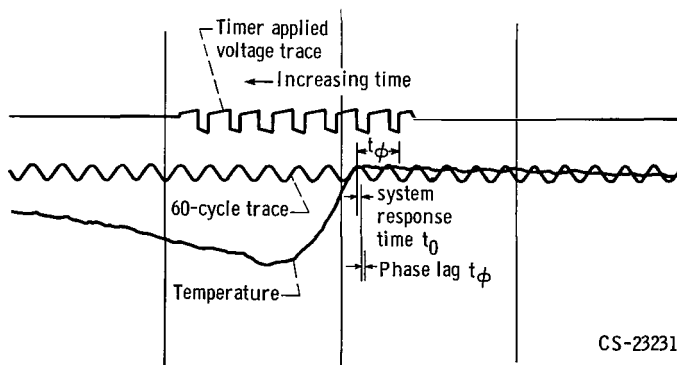


Figure 6. - Oscillograph trace.

(2) The temperature drop indicates that the surface heat flux during growth is approximately 20 times the average heat flux electrically generated in the surface. These data were taken with the 0.0056-inch-thick nickel-chrome alloy ribbon.

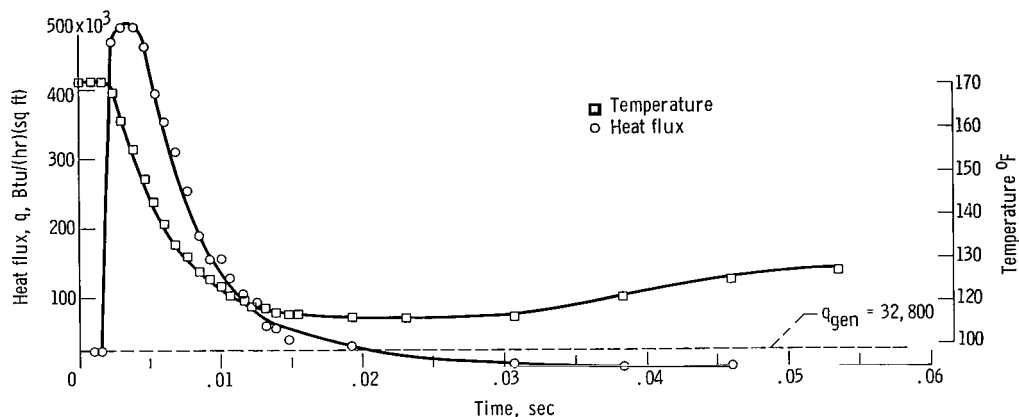
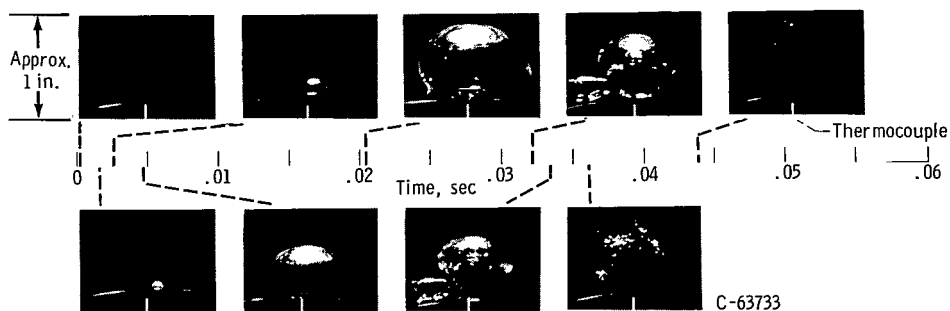
(3) The temperature drop lasts for about 12 milliseconds, a time that is long in comparison to the heater relaxation period of 0.5 millisecond; therefore, the surface cooling mechanism beneath the bubble is considered to be continuous, with a duration of several milliseconds for the bubbles studied. These data were taken with the 0.001-inch-thick nickel-chrome alloy ribbon.

(4) The temperature reaches a minimum as the bubble approaches its maximum diameter. In all cases the temperature drop is completed before bubble collapse.

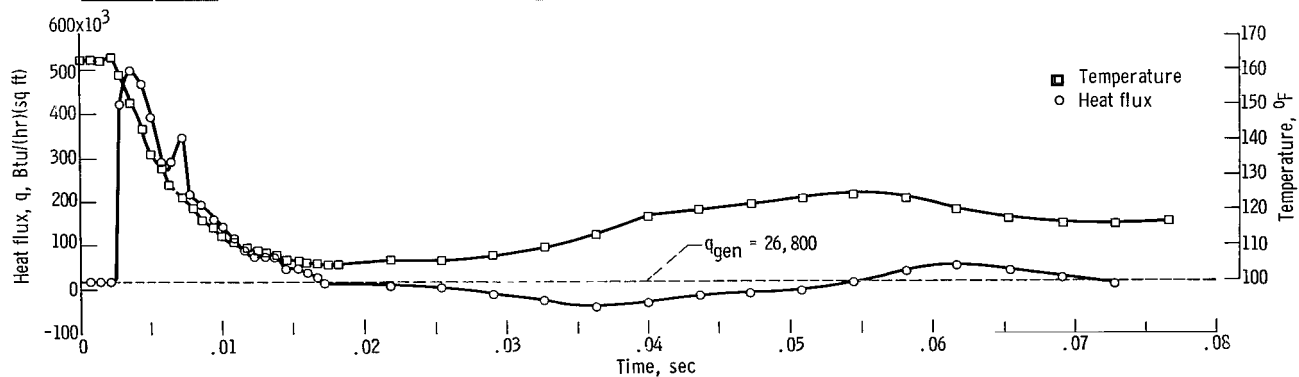
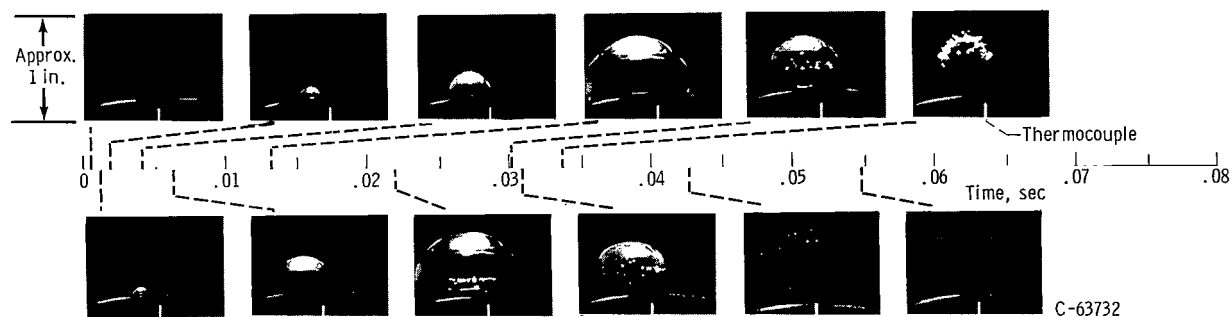
The first and second observations of the temperature drop are consistent with an evaporative phenomenon only. The fact that such rapid cooling occurs directly beneath the bubble cannot be explained by forced convection. The third observation indicates that evaporation occurs continuously from a micro-layer as described by Snyder (ref. 5) and Edwards (ref. 6), rather than solely from the perimeter of the bubble base. Since evaporation in this experiment was limited by the thermal capacity of the heater ribbon, it is possible that under different surface conditions a dry spot might occur within the bubble base. The fourth observation demonstrates that surface cooling in no way depends on a quenching process; this conclusion, however, may not be valid below the subcooling range studied (5° to 20° F). Detailed temperature and heat-flux profiles of two typical bubbles are presented in figure 7.

It can be concluded that the temperature drop is caused by liquid evaporation. In view of the experiments of reference 8, however, which showed that streams of air bubbles can raise the heat-transfer coefficient considerably, it is necessary to examine more closely the effects of bubble agitation. When a bubble leaves the heating surface, turbulence would be expected to be at a peak; yet, surprisingly, the heat flux is quite low and occasionally becomes negative. The reason for this adverse effect of agitation is that the surface, which has been cooled almost to T_{sat} by evaporation, is actually colder than the liquid that quenches it. Conversely, in the case of air bubbles, where there is no evaporation on the heater, quenching will take place over a hot surface; thus, turbulence will be a much more effective means of heat transfer than in actual boiling. This interpretation fits nicely with the results of reference 8, since the air bubbles did affect the heat flux strongly but less strongly than vigorous nucleate boiling did.

Still, the evidence is not quite conclusive that the quenching mechanism is ineffective in all cases of boiling. The heater ribbon used in the present tests had a very small heat capacity, and during bubble formation all the available heat was withdrawn from the surface much more rapidly than it could be restored by electric generation. When boiling takes place on a more massive solid, which has a higher thermal capacity and conductivity, it is possible that the surface temperature after complete evaporation remains appreciably higher than that of the quenching liquid. Under these conditions and in



(a) Generated heat flux, 32,800 Btu per hour per square foot; liquid bulk temperature, 84° F.



(b) Generated heat flux, 26,800 Btu per hour per square foot; liquid bulk temperature, 83° F.

Figure 7. - Temperature and heat flux beneath growing bubble. Saturation temperature, 95° F.

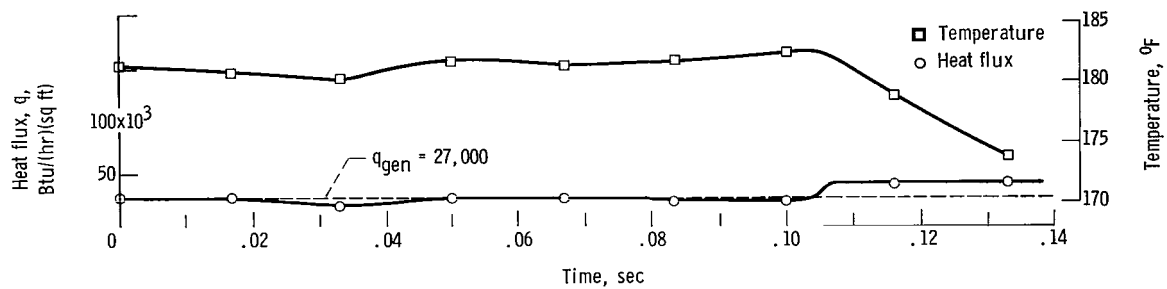
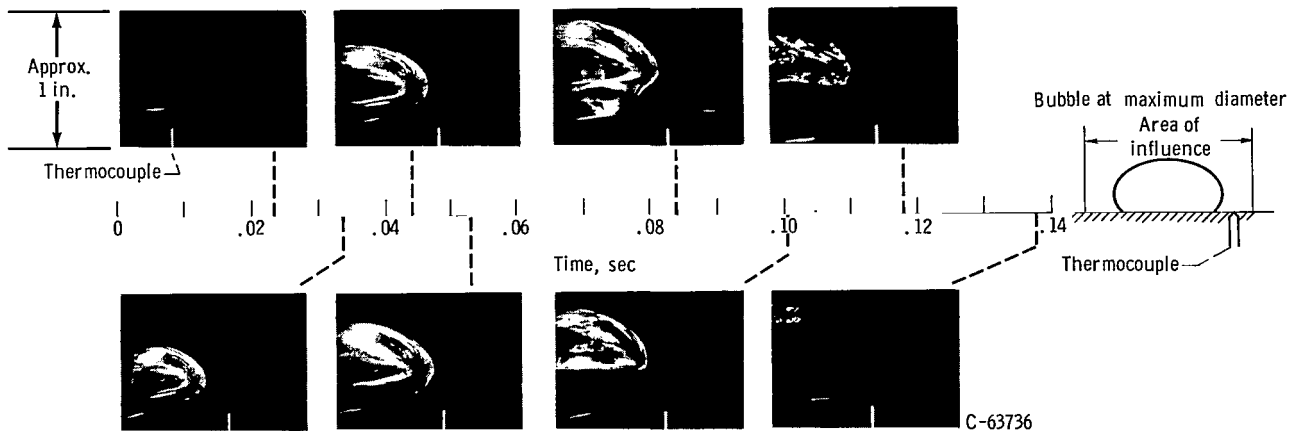
the case of a high degree of subcooling a quenching mechanism might become significant. Whether such rapid heat replenishment into the surface ever occurs in boiling remains to be proved.

Even if the quenching mechanism is inoperable, microconvection in the liquid around the bubble could be an important path of heat transfer. As mentioned previously, it was demonstrated in the work of reference 3 that the thermal layer is greatly diminished over a distance of one bubble diameter around the nucleation site. In order to investigate the direct cooling effect of microconvection, the temperature profiles measured at three adjacent positions in the area of influence were compared (fig. 8 (a), (b), and (c)). In figure 8(a) the thermocouple is slightly less than one bubble diameter away from the nucleation site. No appreciable effect on heat transfer is seen during growth, and there is only a small rise in heat flux during collapse. Increased pool turbulence probably accounts for this rise. In figure 8(b) the bubble base comes very near, but does not cover, the thermocouple junction; the results are similar to those of figure 8(a). In figure 8(c) the edge of the bubble base does pass over the thermocouple, and the rapid temperature drop associated with evaporation can be observed. Figure 8 demonstrates adequately that the direct cooling effect of microconvection due to bubble growth and collapse is small. Increased pool turbulence, by diminishing the thermal layer around the bubble, probably has a sizable indirect effect on the heat transfer. As pointed out in reference 3, the thickness of the thermal layer exercises extensive control over the nucleation capabilities of the surface.

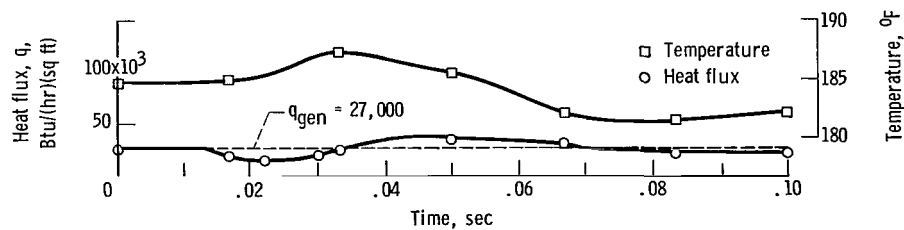
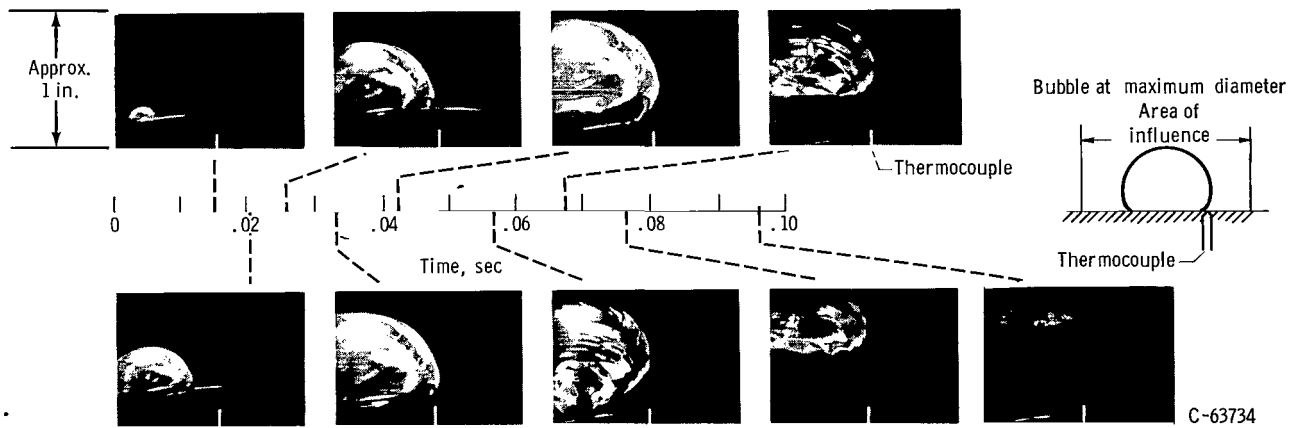
In terms of heat-transfer models, an evaporating microlayer at the base of the bubble is evidently responsible for most of the increased heat flux due to ebullition.³ Neither microconvection nor surface quenching seem to be very important, although increased pool turbulence may well affect both surface cooling and nucleation appreciably. The contribution of ebullition to the total heat transfer seems to depend mostly on the time-average fraction of the surface covered by an evaporating microlayer (i.e., bubbles in the growth stage). When the waiting period is many times the bubble life, free convection will be the dominant heat-transfer mechanism. If, however, the waiting period equals the growth period, practically all the heat from the surface beneath a bubble column will be removed as latent heat. In this case, much of the heat supplied during the waiting period will not leave the solid but must be used to reheat the surface to a temperature sufficient for nucleation.

As an illustration of where the evaporative mechanism becomes effective, consider the boiling case when an average of one-tenth of the surface area is periodically covered by bubbles. If the heat flux through the bubble base is

³An interesting calculation to approximate the thickness of the microlayer can be made by integrating the heat flux over the bubble residence time; enough heat is transferred during the temperature drop to evaporate completely a film 8000 Å thick at the bubble base. The actual layer is probably thicker than this because evaporation into the observed bubble was limited, not by the liquid available in the film, but by the small heat capacity of the heater ribbon.

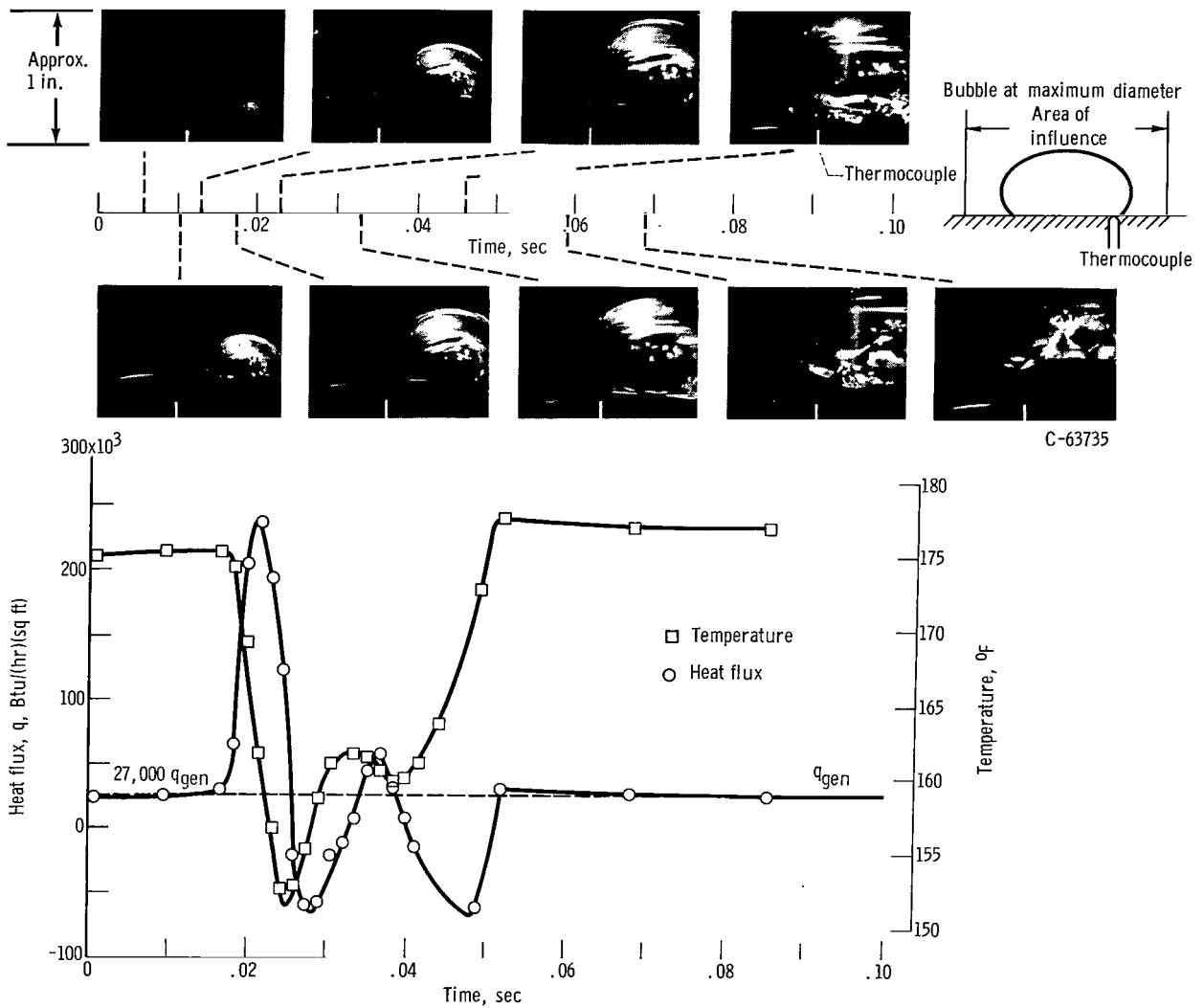


(a) Thermocouple in outer area of influence.



(b) Thermocouple at edge of bubble base.

Figure 8. - Temperature and heat flux in area of influence. Heat flux, 27,000 Btu per hour per square foot.



(c) Thermocouple covered by bubble base.
 Figure 8. - Concluded. Temperature and heat flux in area of influence. Heat flux, 27,000 Btu per hour per square foot.

generally 10 times the gross surface flux, evaporation and convection should have approximately equal effects on the heat transfer. When the surface becomes densely populated with bubble columns, it seems quite likely that latent heat transports as much as 70 to 90 percent of the total heat flux. It is reported in reference 12 that near burnout the fraction of the surface covered by bubbles was 0.4 or greater for distilled water; reference 10 also gives data in the 70 to 90 percent range that were calculated from heat flux.

CONCLUSIONS

The initiation of cooling due to bubble growth on a heating surface was investigated. It may be concluded from comparison of photographic and surface-temperature data that

1. A very rapid temperature drop occurs when the perimeter of the bubble base passes over the thermocouple junction.

2. A twentyfold increase over the average heat flux is observed directly beneath the bubble during the growth period; this surge in heat flux is completed as the bubble reaches its maximum diameter.

3. There is an appreciable decrease in the local heat flux beneath the bubble during collapse.

4. A small, but measurable, rise in heat flux occurs in the area of influence during bubble collapse.

These results show that an evaporative heat-transport mechanism is much more important in nucleate boiling than has been indicated by previous experiments. In particular, strong support is given to the evaporating microlayer hypothesis of Snyder and Edwards. The microconvection and vapor-liquid displacement mechanisms of bubble agitation seem to have very little effect on heat transfer; this conclusion is independent of the heat flux though possibly not of extensive subcooling. Increased turbulence due to bubble collapse has a small direct effect on the heat flux, which may be appreciable in slow boiling. The contribution of bubble formation to the total heat transfer must be considered in relation to the entire ebullition cycle and will depend strongly on the time-average fraction of the surface covered by growing bubbles.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 29, 1964

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